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EVIDENCE FOR STELLAR STREAMING IN THE CORES OF ELLIPTICAL GALAXIES: A KINEMATIC SIGNATURE OF MERGERS?

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ABSTRACT

We present evidence for non-Gaussian velocity fields within the cores of luminous elliptical galaxies. This evidence is based on high signal-to-noise ratio, medium-resolution spectroscopy of the cores of early-type members of the Virgo and Coma Clusters obtained with the Wisconsin-Indiana-Yale-NOAO 3.5 m telescope. The Virgo data were acquired using an integral-field unit (DensePak), which allows the velocity field to be sampled over a variety of spatial scales. The Coma data were obtained through single 2″ diameter fibers. The cross-correlation profiles of luminous elliptical galaxies show considerable structure, often having several features with amplitudes as high as 10% that of the cross-correlation peak itself. This structure is most obvious within a radius of 1″.5 (at Virgo), or ≤100 pc, and is nearly undetectable when the data are binned over $R < 15''$, or ≤1 kpc. Similar features are found in the single-fiber spectra of the luminous elliptical galaxies in the Coma Cluster, suggesting that they are ubiquitous in giant elliptical galaxies. Interestingly, only the most luminous elliptical galaxies show these phenomena; the central regions of lower luminosity elliptical galaxies have regular Gaussian-like profiles. We interpret this kinematic structure as "stellar streaming" and suggest that these phenomena could be a relic signature of the merger history of luminous elliptical galaxies.

Subject headings: galaxies: fundamental parameters — galaxies: kinematics and dynamics — galaxies: nuclei — galaxies: structure

1. PHOTOMETRIC PROPERTIES OF ELLIPTICAL GALAXIES

It is generally accepted that elliptical galaxies are the merger product of smaller mass systems (Toomre 1977). While elliptical galaxies populate a "fundamental plane" in their global scaling properties (e.g., Dressler et al. 1987; Djorgovski & Davis 1987), they also appear to be broadly composed of two families, giants and dwarfs (e.g., Kormendy & Djorgovski 1989). These distinct properties are often assumed to be the result of luminous elliptical galaxies forming from lower luminosity systems through a merger process. Recently, Faber et al. (1997) have shown that the photometric profiles of the cores of elliptical galaxies can also be broadly classified into two groups, those with "cores" and those with "cusps." Systems with cusps have surface brightness profiles that continue to rise into their innermost regions. In contrast, systems with cores have an inner region of almost constant surface brightness, with a well-defined radius in which the profile breaks to form the standard $R^{1/4}$ profile. Core profiles are found exclusively within giant elliptical galaxies, while those systems with photometric cusps are invariably lower luminosity systems. Faber et al. (1997) suggested that the distended cores of the higher luminosity systems could be the result of a kinematic heating of the stellar population supplied by massive black holes (BHs) that survive the merger process. In this scenario, these massive BHs may produce detectable stellar "wakes" as they traverse the background sea of relatively low mass stars.

We have found evidence for non-Gaussian velocity fields within the cores of giant elliptical galaxies. In § 2 we describe our observational data and analysis procedures. In § 3 we introduce a "structure index" in order to quantify the kinematic structure that we find. We present evidence that the structure index is strongly correlated with the absolute magnitude of the galaxy. We discuss some possible interpretations of these phenomena in § 4, and in § 5 we summarize of our results.

2. SPECTROSCOPY OF ELLIPTICAL GALAXIES

High signal-to-noise ratio, medium-resolution spectroscopy of several hundred elliptical galaxies has been obtained with the Wisconsin-Indiana-Yale-NOAO (WIYN) 3.5 m telescope on Kitt Peak as part of an extensive investigation of the fundamental plane of early-type galaxies. The sample presented in this Letter includes the brighter elliptical galaxies in the Virgo and Coma Clusters. The Virgo data were acquired with "DensePak" in order that we may sample these nearby systems over similar spatial scales, as was done with the 2″ fibers for more distant galaxies. DensePak is an integral-field unit consisting of a 7 × 13 array of 3″ diameter fibers that sample a 30″ × 45″ region on the sky (Barden, Sawyer, & Honeycutt 1998). A second fiber bundle consisting of 96 robotically positioned 2″ diameter fibers (Hydra) was used to acquire spectroscopy of the Coma galaxies.

The exposure times using DensePak were typically 30 minutes for each Virgo galaxy, while the Coma data constituted four 1 hr exposures with Hydra. The signal-to-noise ratio was typically about 50 pixel^{-1}. Both fiber bundles feed a versatile, bench-mounted spectrograph enabling a wide variety of configurations. We chose the standard f/6 paraboloid collimator with the refractive f/1.43 "red" camera and the 860 line mm^{-1} grating in second order to produce a reciprocal dispersion of 19.9 Å mm^{-1} or 0.477 Å pixel^{-1} with the Tektronics 2048 × 2048, thinned CCD (T2KC). This configuration produced an FWHM of 2.5 pixels as measured from the comparison lines corresponding to an instrumental velocity resolution (1 σ) of 29 km s^{-1}. We chose the spectral region from 4813–5793 Å, including Hβ, Mg *b*, and Fe + Ca I. Comparison spectra of a CuAr lamp were taken periodically over the course of the night. Flat-field calibration was done on each night using a quartz lamp in order to correct for the fiber-to-fiber sensitivity variations and to define the extraction regions for the individual spectra. Observations of several "super–metal-rich" K giant

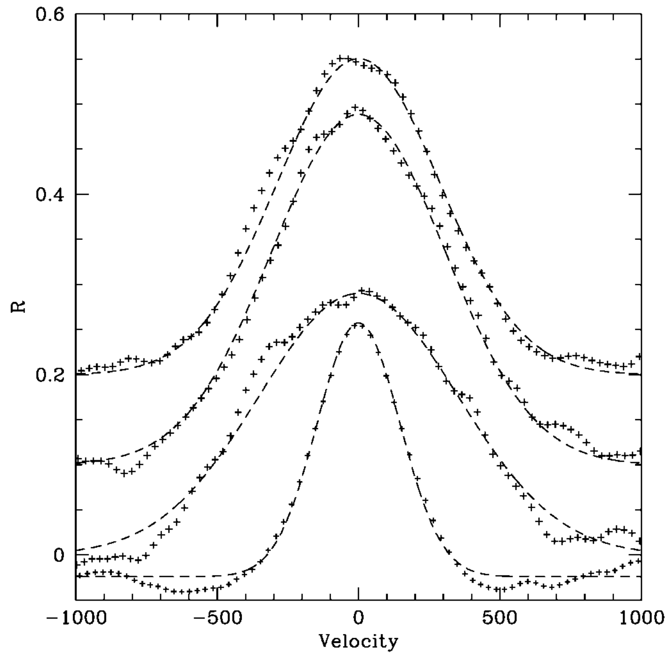

FIG. 1.—Cross-correlation profiles of selected elliptical galaxies in the Virgo and Coma Clusters. From top to bottom are shown NGC 4874 (Coma), NGC 4472 (Virgo), NGC 4486 (Virgo), and TT 41 (Coma). The top two have been offset by 0.1 in the vertical direction, while the bottom plot has been offset by −0.05 and scaled by 0.5. The vertical scale corresponds to NGC 4486 (M87) in Virgo. The plus signs are the data, and the dashed line is the best-fit Gaussian model produced by the IRAF task FXCor. A structure index is defined by counting the number of deviations from the best-fit Gaussian (see text and Fig. 2).

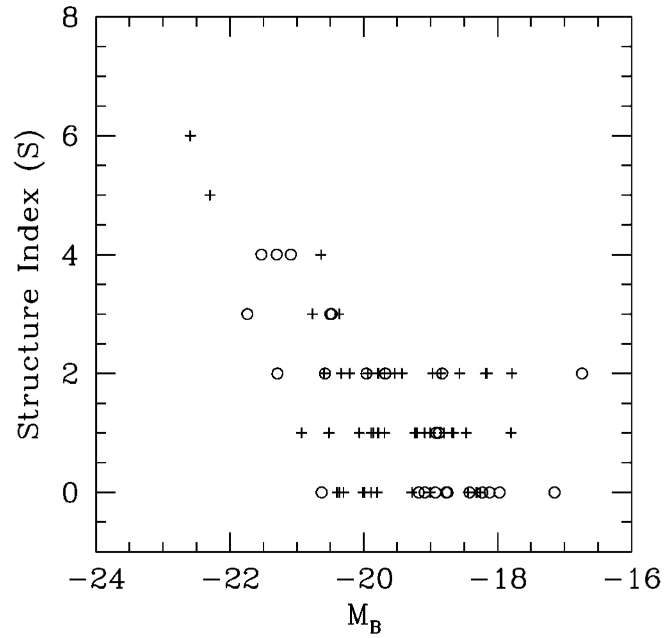

FIG. 2.—Structure index (see text) as a function of galaxy luminosity. The open circles are Virgo galaxies, assuming $(m - M)_{\mathrm{Virgo}} = 31.0$, and the plus signs are Coma Cluster galaxies, assuming $(m - M)_{\mathrm{Coma}} = 34.9$. Evidently, luminous elliptical galaxies within both clusters show an increasing amount of kinematic structure with luminosity.

stars (Faber et al. 1985) were obtained through different fibers over the course of each night. In the case of the DensePak data, we acquired these template stars both in and out of focus in order to test for artifacts introduced by fiber-to-fiber variations in the spectrograph. We also acquired exposures of the twilight sky on each night. The only differences discernible between any of the template and/or twilight exposures were very small and negligible focus variations along the spectrograph slit.

All the spectra were processed and extracted using the "DoHydra" script within IRAF. The flat-field exposures were used to define the apertures for optimal extraction. CuAr comparison spectra were extracted and fitted to provide the wavelength calibration. Sky spectra were extracted and co-added. For the Hydra data, we allocated 25 fibers to the sky, but in the case of DensePak, only four fibers are available for sky. The calibrated and extracted spectra were saved in a "multispec" format for later analysis. We began by computing the median intensities of each of the DensePak spectra. From these, we calculated the intensity-weighted, spatial centroid of the galaxy on the DensePak array. Given the projected position of each fiber on the sky, the spectra were binned over various spatial scales to create summed object spectra. The spectra of the template K giant stars were extracted and cross-correlated with each object spectra using the FXCor task within IRAF. This task is based on the algorithm of Tonry & Davis (1979). The cross-correlation is performed in Fourier space, but any model fitting is done in real space. One advantage of this approach is that the resulting profile is easily compared with a model, in our case a Gaussian, and any deviations are readily apparent.

3. RESULTS

Upon examination of the cross-correlation profiles of the Coma data, we were immediately struck by the presence of strong irregularities in the profiles of the most luminous systems. The DensePak data for Virgo were found to show similar features. We show some selected examples in Figure 1, along with the best-fit Gaussian models. The Coma data were taken over the course of several nights, and the data from each night were reduced independently. We found that the features present in the cross-correlation peak were repeated from night to night. We tried several different K giant stars as templates but could not find any detectable differences in the cross-correlation profiles. For the DensePak data, nearly all the Virgo galaxies were centered on the same fiber of the array. We did find that when the DensePak data were binned over successfully larger radii, the amplitude of the deviations decreased rapidly. Over scales of $R < 15''$, or about 1 kpc, the cross-correlation profiles became highly Gaussian. While it is possible that small asymmetries in the profiles could be introduced by line-strength variations, it seems implausible that such variations can produce the dramatic substructure seen in Figure 1. We therefore conclude that the features we find in the cross-correlation profiles are real and are due to distinct kinematic components in the velocity field of these galaxies.

In an attempt to quantify the degree of substructure in the cross-correlation profiles, we defined a structure index (S). Using the Coma data taken over different nights as a guide, we adopted criteria as to what constituted a significant deviation from the best-fit Gaussian profile. Deviations below the FWHM of the profile were ignored as were any deviations that were centered on the profile peak. We then simply counted the deviations, both negative and positive, from the best-fitting Gaussians. The value of S was estimated by both of us, and any discrepancies were resolved. Figure 2 shows the value of S for each galaxy plotted against its absolute magnitude in *B*. The apparent *B* magnitudes were taken from the RC3 catalogue (de Vaucouleurs et al. 1991) or computed from our unpublished *I*-band photometry assuming a mean $B-I$ color of 2.35. For the Virgo sample, we assumed an average distance modulus of 31.0, and for the Coma sample, we assumed an average distance modulus of 34.9. The spectroscopic and photometric data will be presented in greater detail at a later date. Figure 2 shows a clear trend of *S* increasing with the absolute magnitude of the galaxy for those systems with $M_B \leq -20.0$. Lower luminosity systems have smoother, Gaussian-like velocity fields (i.e., low *S*). Both the Virgo and Coma samples show the trend of increasing *S* with luminosity and a similar "transition luminosity." There is a hint that the lower luminosity systems in Coma may show more structure than do comparable systems in Virgo, but the inherent uncertainty in our index (*S*) prevents a more definitive conclusion.

4. DISCUSSION AND CONCLUSIONS

The kinematic structure that we find within the cores of luminous elliptical galaxies is inconsistent with the smooth, Gaussian profiles expected from classical models for elliptical galaxies (e.g., Binney & Tremaine 1987). One possible explanation is that it is produced by "stellar streaming." However, there may be a problem with the timescale. If we estimate the stellar orbital periods within the cores of luminous elliptical galaxies as their scale (~10 kpc) divided by the velocity dispersion (~300 km s^{-1}), we obtain a typical period of $\sim 10^7$ yr. Since phase mixing is expected to dilute coherence over only a few orbital periods, we estimate the lifetime of such stellar streams to be only a few times 10^7 yr. For comparison, the typical crossing time of the galaxies within these clusters is much longer, $\sim 10^9$ yr. As a result, it seems unlikely that galaxy-galaxy encounters are sufficiently frequent to maintain the kinematic structure that we find.

While there may be alternative scenarios that could produce kinematic structure, we favor a merger scenario. Faber et al. (1997) recently suggested that the existence of multiple BHs could explain the distinction between the photometric profiles of elliptical galaxies. The distended cores for the most luminous systems can be maintained if the BHs presumed to be present in the nuclei of lower luminosity galaxies (e.g., van der Marel 1999) survive the merger process and then heat the stellar distribution through gravitational encounters (e.g., Quinlan & Hernquist 1997). Faber et al. (1997) found that the "break radius," which separates the inner core profile and the outer $R^{1/4}$ profile, correlated strongly with galaxy luminosity; the most luminous systems had the largest cores. Interestingly, the luminosity at which we find the kinematic structure to increase is essentially the same as that found by Faber et al. (1997) for the transition between elliptical galaxies with cores and those with cusps. We interpret this as further evidence that these two phenomena are related. In the context of their model, the kinematic structure that we find might be explained as the "stellar wakes" produced by these BHs as they traverse through the background distribution of stars. We speculate that the increased structure we find within the most luminous systems could reflect a larger number of merger events for these galaxies. If so, an investigation of these phenomena in field environments might be warranted. Furthermore, the development of the *Next Generation Space Telescope* could provide the opportunity of investigating these phenomena at redshifts of ~0.5 and perhaps allow the merger history of luminous elliptical galaxies to be quantified.

5. SUMMARY

We find evidence for kinematic structure within the cores of luminous elliptical galaxies. Lower luminosity systems show smooth Gaussian velocity fields, while the higher luminosity systems show a more irregular velocity field. The structure within luminous systems is most prominent within 100 pc of the center, with smooth Gaussian velocity fields more characteristic of the integrated light within 1 kpc. We define a structure index that is found to be well correlated with the absolute magnitude of the galaxy. We favor an interpretation of these phenomena as resulting from coherent stellar streaming and suggest that it could be a relic signature of the merger history of luminous elliptical galaxies. There have been recent suggestions that luminous elliptical galaxies may harbor several massive BHs that heat the stars and produce the extended luminosity profiles found in these systems. In this scenario, the kinematic substructure reported here could be interpreted as the stellar wakes produced by these BHs.

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